

MARSHALL GRANT
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P. 26

STOCHASTIC MODEL OF THE NASA/MSFC GROUND FACILITY
FOR LARGE SPACE STRUCTURES WITH UNCERTAIN PARAMETERS
- THE MAXIMUM ENTROPY APPROACH

REPORT

by

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NASA Grant Number : NAG8-081
Grant Period : 10-20-86 to 10-19-87

(NASA-CR-181489) STOCHASTIC MODEL OF THE N88-12343
NASA/MSFC GROUND FACILITY FOR LARGE SPACE
STRUCTURES WITH UNCERTAIN PARAMETERS: THE
MAXIMUM ENTROPY APPROACH (Alabama Univ.) Unclas
26 p Avail: NTIS HC A03/MF A01 CSCL 12B G3/66 0106771

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1. INTRODUCTION

The National Aeronautics and Space Administration and the Department of Defense are actively involved in the development of a validated technology data base in the areas of control/structures inter-action, deployment dynamics and system performance for Large Space Structures (LSS). In the Control System Division of the System Dynamics Laboratory of the NASA/MSFC, a Ground Facility (GF), in which the dynamics and control system concepts being considered for LSS applications can be verified, has been designed and built under Dr. Henry Waites' supervision [8]. The viability and versatility of this MSFC LSS ground test facility was recognized by the U. S. Air Force Wright Aeronautical Laboratory as a site for their Vibration Control of Space Structures (VCOSS) testing.

One of the important aspects of the GF is to verify the analytical model for the control system design. The procedure is to describe the control system mathematically as well as possible, then to perform tests on the control system, and finally to factor those results into the mathematical model.

However, development of a "correct" mathematical model of a system is still an art. In constructing large order

structural models, various errors, such as modelling errors, parameter errors, improperly modeled uncertainties, and errors due to linearization of non-linear effect, create a great challenging task of determining "best" models for a dynamic system. It is recognized that it is conceivable that better performance will be anticipated when uncertainties are modeled through stochastic multiplicative and additive noise terms. Optimal control strategies generated under all possible parameter variations will definitely create more robust control systems, under controllability and observability conditions, than those generated by the usual approaches [2]. To avoid ad hoc assumptions regarding "a priori" statistics, Hyland [2,3,4] used the maximum entropy principle to determine a priori probability assignment induced from available data. A main advantage of maximum entropy approach is that it sacrifices as little near-nominal performance as possible while securing performance insensitivity over the likely range of modelling errors.

In this report, we design a stochastic control model of the NASA/MSFC Ground Facility for LSS control verification through the maximum entropy principle adopted in Hyland's method [2,3,4]. Using ORACLS, a computer program is implemented for this purpose. Four models are then tested. Results are presented in this report.

2. MAXIMUM ENTROPY MODELLING

Consider a linear system :

$$\begin{aligned}\dot{X} &= AX + BU + \omega_1 \\ Y &= CX + \omega_2\end{aligned}\tag{1}$$

where

$$X \in R^n, U \in R^m, Y \in R^l, A \in R^{n \times n}, B \in R^{n \times m}, C \in R^{l \times m},$$

and

$$SD(\omega_1, \omega_2) = (v_1, v_2).$$

We seek to determine a dynamic compensator

$$\begin{aligned}\dot{Z} &= A_c Z + FY \\ U &= -KZ\end{aligned}\tag{2}$$

where $Z \in R^n$, $A_c \in R^{n \times n}$, $F \in R^{n \times l}$ and $K \in R^{m \times n}$ that minimizes the Quadratic Cost Function :

$$J = \int_0^{\infty} (X^T R_1 X + U^T R_2 U) dt\tag{3}$$

where R_1 and R_2 are penalty matrices. The maximum entropy (ME) design approach [1,2,3,4,5] is used to minimize J in the presence of parameter uncertainties.

In most instances, the actual system dynamics differ from the nominal model by an error distribution matrix. The basic premise of ME error modelling is that the magnitude of the error is a white-noise process $\alpha(t)$. Assuming there are p uncorrelated error sources, the system dynamic matrices

become :

$$A_{\text{actual}} = A + \sum_{i=1}^p \alpha_i(t) A_i \quad (4)$$

with the B_{actual} and C_{actual} matrices taking similar forms.

For the simplicity and in order to get a good inside look at the ME design technique, we assume there is only one error distribution matrix A_1 in the system. Under these assumption, the necessary conditions for optimality of the Quadratic Cost Function can be derived after the system dynamics are presented by means of stochastic differential equations. The resulting equations take the form of two Riccati equations and two Lyapunov equations, all coupled by the stochastic parameters [6]. That is, we need to solve four nonnegative-definite P , Q , \hat{P} and \hat{Q} such that

$$\begin{aligned} P A_S + A_S^T P + A_1^T P A_1 - P_S^T R_2^{-1} P_S + R_1 + A_1^T \hat{P} A_1 &= 0 \\ A_S Q + Q A_S^T + A_1 Q A_1^T - Q_S V_2^{-1} Q_S^T + V_1 + A_1 \hat{Q} A_1^T &= 0 \\ \hat{P} A_{QS} + A_{QS}^T \hat{P} + P_S^T R_2^{-1} P_S &= 0 \\ A_{ps} \hat{Q} + \hat{Q} A_{ps}^T + Q_S V_2^{-1} Q_S^T &= 0 \end{aligned} \quad (5)$$

where

$$\begin{aligned} A_S &\triangleq A + \frac{1}{2} A_1^2, \quad P_S \triangleq B^T P, \quad Q_S \triangleq Q C^T, \\ A_{QS} &\triangleq A_S - Q_S V_S^{-1} C, \quad A_{ps} \triangleq A_S - B R_2^{-1} B^T P. \end{aligned}$$

The compensator matrices then take on the following forms,

$$A_c = A_s - Q_s V_2^{-1} C - B R_2^{-1} P_s$$

$$F = Q_s V_2^{-1} \quad (6)$$

$$K = R_2^{-1} P_s.$$

Unfortunately, the covariance matrices V_1 and V_2 of the Wiener processes ω_1 and ω_2 , respectively, in (1) are usually not known. However, we developed a method of estimating those two import matrices as follows.

Consider the system

$$\dot{X} = AX + BU + \omega_1. \quad (7)$$

(7) can be rewritten as

$$dx^i = \left(\sum_j A_j^i x^j + \sum_k B_k^i U^k \right) dt + d\omega_1^i, \quad i = 1, \dots, n.$$

Let $r_1^{ij} = E[X^i X^j]$ and $r_1^{ij} = E[X^i X^j]$. By Ito's rule, we have

$$\begin{aligned} d(X^i X^j) &= (dx^i) X^j + X^i (dx^j) + (dx^i) (dx^j) \\ &= \left(\sum_k A_k^i X^k X^j + \sum_l B_l^i U^l X^j \right) dt \\ &\quad + \left(\sum_k A_k^j X^k X^i + \sum_l B_l^j U^l X^i \right) dt \\ &\quad + X^j d\omega_1^i + X^i d\omega_1^j + (d\omega_1^i) (d\omega_1^j). \end{aligned} \quad (8)$$

With the assumption that X and ω_1 are uncorrelated, (8) becomes

$$\dot{r}^{ij} = \sum_k A_k^i r^{kj} + \sum_k A_k^j r^{ki} + \sum_l B_l^i q^{lj} + \sum_l B_l^j q^{kl} + V_1^{ij}$$

or

$$V_1^{ij} = \sum_k A_k^i r^{kj} + \sum_k A_k^j r^{ki} + \sum_l B_l^i q^{lj} + \sum_l B_l^j q^{kl} - \dot{r}^{ij}, \quad (9)$$

where $V_1^{ij} dt = E[d\omega_1^i d\omega_1^j]$ and $q^{ij} = E[U^i X^j]$.

If we assume, in addition, that X and U are uncorrelated, then we can drop the terms involving q^{ij} in (9). And (9) becomes

$$V_1^{ij} = \sum_k A_k^i r^{kj} + \sum_k A_k^j r^{ki} - \dot{r}^{ij} \quad (10)$$

for $i, j = 1, 2, \dots, n$.

Therefore, if r and \dot{r} can be estimated, then the covariance matrix V_1 can be estimated through (10).

Estimation of V_2 for ω_2 in the equation $Y = CX + \omega_2$ is a much easier job. We simply use the standard statistics technique to estimate V_2 by $E[(Y - CX)(Y - CX)^T]$.

3. COMPUTATION ALGORITHM

In this report, we treat all four equations in (5) together as a single Riccati equation. This approach is different from the one proposed by Gruzen [6] in which each iteration involves solving the first two equations of (5) as Riccati equations and then solving the last two equations of (5) as Lyapunov equations.

We can rewrite (5) as following:

$$\begin{aligned}
 PA_S + A_S^T P - P^T B R_2^{-1} B^T P + A_1^T (P + (A_1^{-1})^T R_1 A_1^{-1} + \hat{P}) A_1 &= 0 \\
 QA_S^T + A_S Q - Q C^T V_2^{-1} C Q + A_1 (Q + A_1^{-1} V_1 (A_1^{-1})^T + \hat{Q}) A_1^T &= 0 \\
 \hat{P} A_{QS} + A_{QS}^T \hat{P} - \hat{P}^T \theta R_2^{-1} \theta^T \hat{P} + P_S^T R_2^{-1} P_S &= 0 \\
 \hat{Q} A_{PS}^T + A_{PS} \hat{Q} - \hat{Q} \theta V_2^{-1} \theta^T \hat{Q} + Q_S V_1^{-1} Q_S^T &= 0
 \end{aligned} \tag{11}$$

where matrix θ indicates zero matrix with appropriate dimension. In a more concise form, we have:

$$P^* A^* + (A^*)^T P^* - (P^*)^T B^* (R^*)^{-1} (B^*)^T P^* + (H^*)^T Q^* H^* = 0 \tag{12}$$

where

$$\begin{aligned}
 P^* &= \begin{bmatrix} P^T & & 0 \\ & Q & \hat{P} \\ 0 & & \hat{Q} \end{bmatrix}, & R^* &= \begin{bmatrix} R_2 & & 0 \\ & V_2 & \\ 0 & & R_2 & V_2 \end{bmatrix}, \\
 A^* &= \begin{bmatrix} A_S & & 0 \\ & A_S^T & \\ 0 & & A_S & A_{PS}^T \end{bmatrix}, & B^* &= \begin{bmatrix} B & & 0 \\ & C^T & \\ 0 & & \theta \end{bmatrix},
 \end{aligned}$$

$$H^* = \begin{bmatrix} A_1 & A_1^T & 0 \\ 0 & P_S & Q_S^T \end{bmatrix}$$

and

$$Q^* = \begin{bmatrix} P + (A_1^{-1})^T R_1 A_1^{-1} + \hat{P} & 0 \\ Q + A_1^{-1} V_1 (A_1^{-1})^T + \hat{Q} & R_2^{-1} \\ 0 & V_2^{-1} \end{bmatrix}.$$

Note that (12) does not exactly match the standard algebraic Riccati equation form:

$$PA + A^T P - PBR_2^{-1} B^T P + R_1 = 0. \quad (13)$$

Because there are unknown parameters in the last term $H^{*T} Q^* H^*$ in (12). This character affects the iteration scheme significantly. The constant term of the Riccati equation (12) includes P^* matrix. Consequently, the equation must be iterated through several times, updating P^* solution in the constant term each time until it converges to a solution. The iteration strategy is illustrated in Figure 1.

The convergence criterion used in our program is when

$$\| P^{*(n)} - P^{*(n-1)} \| < \epsilon, \text{ where } \epsilon \text{ is a preset tolerance.}$$

The software package ORACLS [7] provides a control system design and analysis environment. This package provides subroutines such as basic matrix manipulations (addition, subtraction, multiplication, transpose, etc.) and Riccati solver. The design algorithm is implemented in FORTRAN (see Appendix).

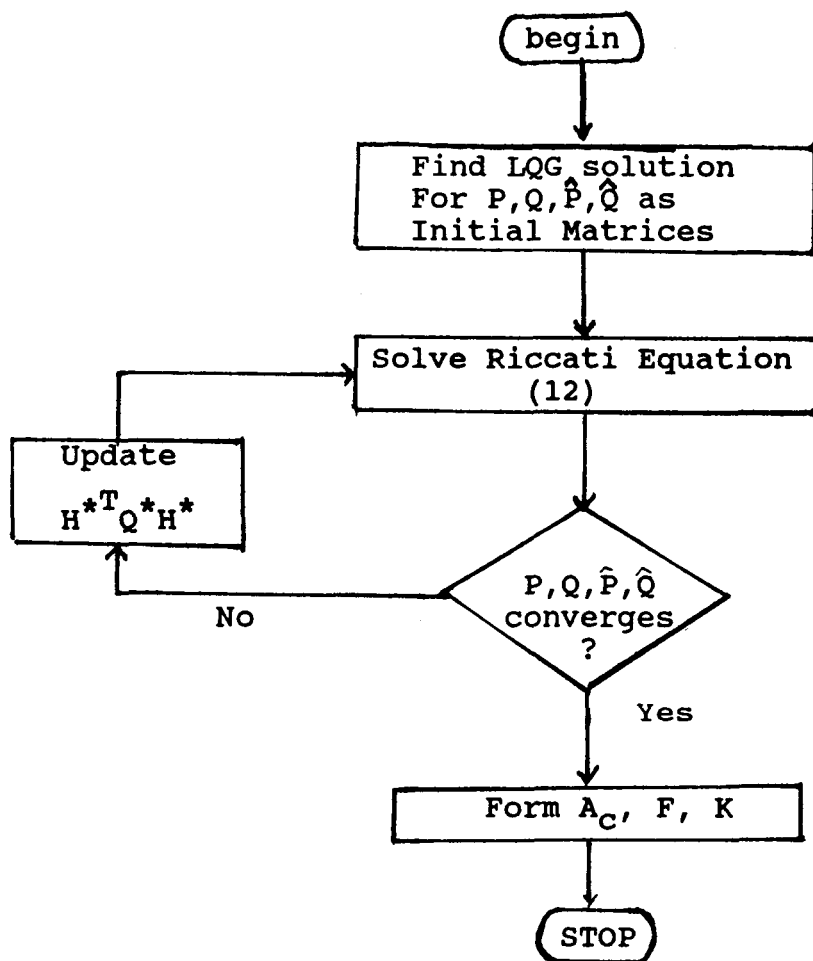


Figure 1

4. COMPUTATION RESULTS OF ME DESIGN

In this section, we applied the ME design algorithm to the MSFC Ground Test Facility in which dynamics and control system concepts being considered for LSS applications can be verified [8].

There are 50 modes in the system model. For the purpose of testing the algorithm and the FORTRAN program, we only consider stochastic models with only one mode. Mode 8 is chosen for this purpose. We also assume there is only one error distribution matrix of A in the system.

Therefore, the stochastic model concerned in this section is

$$\begin{aligned}\dot{X}(t) &= (A + \alpha_1(t)A_1)X(t) + BU(t) + \omega_1(t) \\ Y(t) &= CX(t) + \omega_2(t)\end{aligned}\tag{14}$$

Data collected from an analytical model in four different settings have been provided by Dr. Henry Waites. Using those data, we designed four settings and through which we can determine corresponding compensator matrices. In all of those four settings, we choose the modal damping $\xi_8 = 0.5\%$,

$$R_1 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \text{and} \quad R_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}.$$

The dynamic matrices of those four models are:

Model 1 (EXP5VL Sept. 24. 1986): $\omega_8^2 = 17.44$

$$A = \begin{bmatrix} 0 & 1 \\ -17.44 & -0.04176 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ -0.00154 & 0 & 0 & 0.01 & 0.000176 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 \\ 0 & 0.1 \\ 0 & 0.000176 \end{bmatrix}.$$

Model 2 (EXP6UL Oct. 1. 1986): $\omega_8^2 = 17.44$

$$A = \begin{bmatrix} 0 & 1 \\ -17.44 & -0.04176 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0.0016 & 0 & 0 & -0.01036 & -0.0004875 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0 \\ 0 & -0.01036 \\ 0 & -0.0004875 \end{bmatrix}.$$

Model 3 (EMVL Dec. 29. 1986): $\omega_8^2 = 19.41$

$$A = \begin{bmatrix} 0 & 1 \\ -19.41 & -0.04176 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0.0001 & 0 & 0.002 & -0.0082 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 0.002 \\ 0 & -0.082 \\ 0 & 0 \end{bmatrix}.$$

Model 4 (EMFVLL Jan. 20. 1987): $\omega_8^2 = 14.4$

$$A = \begin{bmatrix} 0 & 1 \\ -14.4 & -0.03796 \end{bmatrix}, \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0.00031890 & 0 & 0 & 0.001617 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 0 \\ 0 & 0.0016171 \\ 0 & 0 \end{bmatrix}.$$

As pointed out by Gruzen [6], we can scale the position coordinate by the modal frequency ω_8 , the first equation of (14) is transformed into an equivalent representation:

$$\frac{d\tilde{X}}{dt} = \begin{bmatrix} 0 & \omega_8 \\ -\omega_8 & -2\xi\omega_8 \end{bmatrix} \tilde{X} + BU, \quad (16)$$

where $\tilde{X} = \begin{bmatrix} x\omega_8 \\ \dot{x} \end{bmatrix}$ with the transformation matrix $T = \begin{bmatrix} \omega_8 & 0 \\ 0 & 1 \end{bmatrix}$.

Therefore, we can assume the uncertainty distribution matrix for the last four models takes the following form:

$$A_1 = \begin{bmatrix} 0 & 1 \\ -1 & -0.01 \end{bmatrix}.$$

The compensation matrices resulted from the algorithm are summerized as following.

Model	1	2
P	3.91 D+04 -2.50 D-03 -2.50 D-03 3.91 D+04	3.63 D+04 -2.50 D-03 -2.50 D-03 3.63 D+04
Q	4.01 D+02 -2.00 D+00 -2.00 D+00 4.01 D+02	3.72 D+04 -1.85 D+02 -1.86 D+02 3.72 D+04
P	1.47 D-06 4.88 D-09 4.83 D-09 1.95 D-11	1.58 D-06 5.26 D-09 5.26 D-09 2.10 D-11
Q	0 0 0 0	0 0 0 0
A _C	-5.0 D-01 2.39 D-03 1.07 D-06 -6.51 D+00	-5.0 D-01 2.39 D-03 1.15 D-06 -6.50 D+00
F	-6.02 D+01 0 6.88 D+00 0 3.91 D+02 7.05 D-02	5.81D+01 0 -1.77D+01 0 -3.76D+02 -1.81D+01
K	3.85 D-06 -6.02 D+01 0 0 0 0 -2.50 D-05 3.91 D+02 -4.40 D-07 6.88 D+00	-4.0 D-06 5.81 D+01 0 0 0 0 2.59 D-05 -3.76 D+02 1.22 D-06 -1.77 D+01

Model	3				4			
P	5.61 D+04	-2.50 D-03			1.47 D+06	-2.50 D-03		
	-2.50 D-03	5.61 D+04			-2.50 D-03	1.47 D+06		
Q	5.61 D+04	-2.81 D+02			1.53 D+06	-7.65 D+03		
	-2.81 D+02	5.61 D+04			-7.65 D+03	1.53 D+06		
\tilde{P}	5.61 D+04	-2.50 D-03			1.47 D+06	-2.50 D-03		
	-2.50 D-03	5.61 D+04			-2.50 D-03	1.47 D+06		
\tilde{Q}	0	0			0	0		
	0	0			0	0		
A_C	-5.0 D-01	2.27 D-03			-5.0 D-01	2.64 D-03		
	7.85 D-07	-6.50 D+00			2.58 D-08	1.47 D+00		
F	5.61 D+00	1.12 D+02	0		4.70 D+02	0	0	
	0	-4.60 D+02	0		0	2.38 D+03	0	
K	-2.50 D-07	5.61 D+00			-7.97 D-07	4.70 D+02		
	0	0			0	0		
	-5.00 D-06	1.12 D+02			0	0		
	2.05 D-05	-4.60 D+02			-4.04 D-06	2.38 D+03		
	0	0			0	0		

Figure 2

5. CONCLUSION

In general, the major issues relevant to the control of flexible space structures are "robustness" with respect to both parameter modelling errors and truncation of higher order modes. Several methods have been developed recently to deal with those problems. Among them, the maximum entropy and optimal projection (MEOP) method developed by Hyland and Bernstein specifically for the flexible structure control problems seems very promising.

In this report, we examined the ME portion of the design method. Using ORACLS, we implemented a computer program for ME method. Four small scaled models are then tested and the resulted compensation matrices are given.

The extension of this project, naturally, would be to test the OP portion of the design method and then combine those two programs to have a complete MEOP design tool.

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APPENDIX 1

COMPUTER PROGRAM FOR ME DESIGN

```

C*****
C*   DRIVER FOR THE MAXIMUM ENTROPY DESIGNER
C*   INPUTTAPE = 5      OUTPUTTAPE = 6
C*****
      IMPLICIT REAL*8 (A-H,O-Z)
      DIMENSION P1(64),A1(64),B1(64),R1(64),Q1(64),H1(64),F1(64),
1         DUMMY(2100),P(4),Q(4),PHAT(4),QHAT(4),E1(4)
      DIMENSION NP1(2),NA1(2),NB1(2),NR1(2),NQ1(2),NH1(2),NF1(2),
1         IOP(3),NE1(2)
      DIMENSION P2(64),A2(64),B2(64),R2(64),Q2(64),H2(64),F2(64),
1         D21(64),D22(64),D23(64),D24(64),D25(64),D26(64)
      DIMENSION NP2(2),NA2(2),NB2(2),NR2(2),NQ2(2),NH2(2),NF2(2),
1         ND21(2),ND22(2),ND23(2),ND24(2),ND25(2),ND26(2)
      DIMENSION A5(4),A51(4),Q5(4),P5(4),Q55(4),P55(4),C5(6),B5(10),
1         V51(4),V52(9),R51(4),R52(25),V152(9),R152(25),B3(256),
1         R3(256),TH3(96),TH4(64),TH5(96),TH6(96),TH7(192),
1         TH8(64),H3(256),TA51(4),TA5(4),A31(4),A32(4),TA6(6),
1         TC5(6),A33(4),TB5(10),TA7(10),A34(4),Z1(12),Z2(8),
1         Z5(128),X1(16),X21(8),X2(16),X31(12),X3(16),X5(32),
1         X6(48),X7(64),X8(128),Q31(4),Q32(4),Z6(20),Z7(20),
1         Z8(15),Z9(27),X9(24),X10(24),X11(60),X12(36),X13(45),
1         X14(48),X15(108),X16(144),X17(48),Q3(256),F3(256),
1         P3(256),X4(16),X18(192),A3(256),TP4(256),TP5(256),
1         PP(4),PPH(4),QQ(4),QQH(4),R15(64),TM1(4),F(6),TM2(4),
1         TM3(10),TM4(10),K(10),E2(4),ACC(4),TRN(4),TRNI(4),AC(4)
      DIMENSION NA5(2),NA51(2),NQ5(2),NP5(2),NQ55(2),NP55(2),NC5(2),
1         NB5(2),NV51(2),NV52(2),NR51(2),NR52(2),NVI52(2),
1         NRI52(2),NB3(2),NR3(2),NTH3(2),NTH4(2),NTH5(2),NTH6(2),
1         NTH7(2),NTH8(2),NH3(2),NTA51(2),NTA5(2),NA31(2),NA32(2),
1         NTA6(2),NTC5(2),NA33(2),NTB5(2),NTA7(2),NA34(2),NZ1(2),
1         NZ2(2),NZ5(2),NX1(2),NX2(2),NX21(2),NX31(2),NX3(2),
1         NX5(2),NX6(2),NX7(2),NX8(2),NQ31(2),NQ32(2),NZ6(2),
1         NZ7(2),NZ8(2),NZ9(2),NX9(2),NX10(2),NX11(2),NX12(2),
1         NX13(2),NX14(2),NX15(2),NX16(2),NX17(2),NX18(2),
1         NQ3(2),NF3(2),NP3(2),NX4(2),NA3(2),NTP4(2),NTP5(2),
1         NP(2),NQ(2),NPHAT(2),NQHAT(2),NPP(2),NPPH(2),NQQ(2),
1         NQQH(2),NR15(2),NTM1(2),NF(2),NTM2(2),NTM3(2),NTM4(2),
1         NK(2),NE2(2),NACC(2),NTRN(2),NTRNI(2),NAC(2)
      INTEGER   IERR,ITE
      REAL      SCLE,EPSI
      LOGICAL   IDENT,DISC,FNULL

C
C   INPUT HOLLERITH DATA FOR TITLE OF OUTPUT
      CALL RDTITL

C
C   TO OBTAIN INITIAL P AND Q BY SOLVING THE ASSOCIATED RCT EQA
C   FROM LQG METHOD
C
C   INPUT COEFFICIENT MATRICES FOR THE INITIAL LQG SYSTEM
C
      CALL READ(4,A5,NA5,A51,NA51,C5,NC5,B5,NB5)
      CALL READ(4,V51,NV51,V52,NV52,R51,NR51,R52,NR52)
      CALL READ(4,A1,NA1,B1,NB1,R1,NR1,Q1,NQ1)
      CALL READ(2,D22,ND22,R15,NR15)
      CALL READ(4,B3,NB3,R3,NR3,TH3,NTH3,TRN,NTRN)
      DO 10 I=1,2
      NVI52(I)=3
      NRI52(I)=5
      NH1(I)=8
      NQ2(I)=8

```

ORIGINAL PAGE IS
OF POOR QUALITY

RCT00010
RCT00020
RCT00030
RCT00040
RCT00050
RCT00060
RCT00070
RCT00080
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RCT00110
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RCT00130
RCT00140
RCT00150
RCT00160
RCT00170
RCT00180
RCT00190
RCT00200
RCT00210
RCT00220
RCT00230
RCT00240
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RCT00460
RCT00470
RCT00480
RCT00490
RCT00500
RCT00510
RCT00520
RCT00530
RCT00540
RCT00550
RCT00560
RCT00570
RCT00580
RCT00590
RCT00600

	ND23(I)=8	RCT00610
	NTH4(I)=8	RCT00620
	NP2(I)=8	RCT00630
	NA2(I)=8	RCT00640
	NB2(I)=8	RCT00650
	NH2(I)=8	RCT00660
	NF2(I)=8	RCT00670
	ND21(I)=8	RCT00680
	ND24(I)=8	RCT00690
	ND25(I)=8	RCT00700
	ND26(I)=8	RCT00710
	NP5(I)=2	RCT00720
	NP55(I)=2	RCT00730
	NQ5(I)=2	RCT00740
	NQ55(I)=2	RCT00750
	NTRNI(I)=2	RCT00760
10	CONTINUE	RCT00770
	CALL UNITY(VI52,NVI52)	RCT00780
	CALL GAUSEL(3,3,V52,3,VI52,IERR)	RCT00790
	CALL UNITY(RI52,NRI52)	RCT00800
	CALL GAUSEL(5,5,R52,5,RI52,IERR)	RCT00810
	CALL EQUATE(R1,NR1,R2,NR2)	RCT00820
	CALL UNITY(Q2,NQ2)	RCT00830
	CALL GAUSEL(8,8,R1,8,Q2,IERR)	RCT00840
	CALL UNITY(D23,ND23)	RCT00850
	CALL GAUSEL(8,8,R15,8,D23,IERR)	RCT00860
	CALL PRNT(VI52,NVI52,4HVI52,1)	RCT00870
	CALL PRNT(RI52,NRI52,4HRI52,1)	RCT00880
	CALL PRNT(R2,NR2,4H R2,1)	RCT00890
	CALL PRNT(Q2,NQ2,4H Q2,1)	RCT00900
	CALL PRNT(D23,ND23,4H D23,1)	RCT00910
	CALL UNITY(TRNI,NTRNI)	RCT00920
	CALL GAUSEL(2,2,TRN,2,TRNI,IERR)	RCT00930
	CALL PRNT(TRNI,NTRNI,4HTRNI,1)	RCT00940
	EPSI=0.001	RCT00950
	DIFF=100.0	RCT00960
C		RCT00970
C	CHECK IF A IS ASYMPOTICALLY STABLE BY CSTAB	RCT00980
C		RCT00990
	IOP(1)=0	RCT01000
	IOP(2)=0	RCT01010
	IOP(3)=0	RCT01020
	SCLE=1.0	RCT01030
	CALL CSTAB(A1,NA1,B1,NB1,F1,NF1,IOP,SCLE,DUMMY)	RCT01040
C		RCT01050
C	READY TO CALL SUBROUTINE RICNWT	RCT01060
	IDENT=.TRUE.	RCT01070
	DISC=.FALSE.	RCT01080
	FNULL=.FALSE.	RCT01090
	DO 50 I=1,550	RCT01100
	DUMMY(I)=0.0	RCT01110
50	CONTINUE	RCT01120
	CALL RICNWT(A1,NA1,B1,NB1,H1,NH1,Q1,NQ1,R1,NR1,F1,NF1,P1,	RCT01130
1	NP1,IOP,IDENT,DISC,FNULL,DUMMY)	RCT01140
C		RCT01150
C	BEGINNING OF THE STEP 2	RCT01160
C		RCT01170
	PRINT *, ' '	RCT01180
C		RCT01190
C		RCT01200

C	CREATE MATRIX D21	RCT01210
C		RCT01220
	DO 20 I=1,64	RCT01230
	D21(I)=0.0	RCT01240
	D26(I)=0.0	RCT01250
20	CONTINUE	RCT01260
	D21(1) =P1(19)	RCT01270
	D21(9) =P1(27)	RCT01280
	D21(2) =P1(20)	RCT01290
	D21(10) =P1(28)	RCT01300
	D21(19) =P1(1)	RCT01310
	D21(27) =P1(9)	RCT01320
	D21(20) =P1(2)	RCT01330
	D21(28) =P1(10)	RCT01340
C		RCT01350
C	CREAT MATRIX B2	RCT01360
C		RCT01370
	CALL NULL(B2,NB2)	RCT01380
C		RCT01390
C	CREATE MATRIX A2	RCT01400
C		RCT01410
	CALL TRANP(D22,ND22,D24,ND24)	RCT01420
	CALL MULT(D23,ND23,D24,ND24,D25,ND25)	RCT01430
	CALL MULT(D22,ND22,D25,ND25,D24,ND24)	RCT01440
	CALL MULT(D21,ND21,D24,ND24,D25,ND25)	RCT01450
	CALL SUBT(A1,NA1,D25,ND25,A2,NA2)	RCT01460
C		RCT01470
C	CREATE MATRIX H2)	RCT01480
C		RCT01490
	D26(1)=P1(1)	RCT01500
	D26(2)=P1(2)	RCT01510
	D26(9)=P1(9)	RCT01520
	D26(10)=P1(10)	RCT01530
	D26(22) =P1(19)	RCT01540
	D26(30) =P1(27)	RCT01550
	D26(23) =P1(20)	RCT01560
	D26(31) =P1(28)	RCT01570
	CALL TRANP(B1,NB1,D22,ND22)	RCT01580
	CALL MULT(D22,ND22,D26,ND26,H2,NH2)	RCT01590
C		RCT01600
C	CHECK IF A2 IS ASYMPTICALLY STABLE BY CSTAB	RCT01610
C		RCT01620
	CALL CSTAB(A2,NA2,B2,NB2,F2,NF2,IOP,SCLE,DUMMY)	RCT01630
C		RCT01640
C	READY TO CALL RICNWT TO FIND P2	RCT01650
C		RCT01660
	IDENT=.FALSE.	RCT01670
	DO 60 I=1,550	RCT01680
	DUMMY(I)=0.0	RCT01690
60	CONTINUE	RCT01700
	CALL RICNWT(A2,NA2,B2,NB2,H2,NH2,Q2,NQ2,R2,NR2,F2,NF2,P2,NP2,	RCT01710
	1IOP,IDENT,DISC,FNULL,DUMMY)	RCT01720
	ITE=0	RCT01730
C		RCT01740
C	END OF SEARCHING INITIAL MATRICES BY LQG	RCT01750
C		RCT01760
	PRINT *, ' '	RCT01770
	PRINT *, ' '	RCT01780
	PRINT *, '*** STARTING LQG SOLUTIONS ARE :'	RCT01790
C		RCT01800

20

C
C
C

START ITERATIVE ALGORITHM

```

P5(1)=P1(1)
P5(2)=P1(2)
P5(3)=P1(9)
P5(4)=P1(10)
P55(1)=P2(1)
P55(2)=P2(2)
P55(3)=P2(9)
P55(4)=P2(10)
Q5(1)=P1(19)
Q5(2)=P1(20)
Q5(3)=P1(27)
Q5(4)=P1(28)
Q55(1)=P2(19)
Q55(2)=P2(20)
Q55(3)=P2(27)
Q55(4)=P2(28)
CALL EQUATE(P5,NP5,P,NP)
CALL EQUATE(P55,NP55,PHAT,NPHAT)
CALL EQUATE(Q5,NQ5,Q,NQ)
CALL EQUATE(Q55,NQ55,QHAT,NQHAT)
CALL EQUATE(P5,NP5,PP,NPP)
CALL EQUATE(P55,NP55,PPH,NPPH)
CALL EQUATE(Q5,NQ5,QQ,NQQ)
CALL EQUATE(Q55,NQ55,QQH,NQQH)
PRINT *, ' '
CALL PRNT(P,NP,4H   P,1)
PRINT *, ' '
CALL PRNT(Q,NQ,4H   Q,1)
PRINT *, ' '
CALL PRNT(PHAT,NPHAT,4H PHAT,1)
PRINT *, ' '
CALL PRNT(QHAT,NQHAT,4H QHAT,1)

```

C
C
C

CREATE H*

```

NTH4(1)=8
NTH4(2)=8
CALL UNITY(TH4,NTH4)
TH4(37)=P1(1)
TH4(38)=P1(2)
TH4(45)=P1(9)
TH4(46)=P1(10)
TH4(55)=P1(19)
TH4(56)=P1(20)
TH4(63)=P1(27)
TH4(64)=P1(28)

```

GO TO 110

100

```

ITE=ITE+1
PRINT *, ' '
PRINT *, ' '
PRINT *, ' '
PRINT *, ' '
PRINT *, ' '
PRINT *, ' '
PRINT *, ' ***** THIS IS ITERATION ',ITE,' *****'
PRINT *, ' '
PRINT *, ' *** NEW SOLUTIONS ARE **'

```

```

RCT01810
RCT01820
RCT01830
RCT01840
RCT01850
RCT01860
RCT01870
RCT01880
RCT01890
RCT01900
RCT01910
RCT01920
RCT01930
RCT01940
RCT01950
RCT01960
RCT01970
RCT01980
RCT01990
RCT02000
RCT02010
RCT02020
RCT02030
RCT02040
RCT02050
RCT02060
RCT02070
RCT02080
RCT02090
RCT02100
RCT02110
RCT02120
RCT02130
RCT02140
RCT02150
RCT02160
RCT02170
RCT02180
RCT02190
RCT02200
RCT02210
RCT02220
RCT02230
RCT02240
RCT02250
RCT02260
RCT02270
RCT02280
RCT02290
RCT02300
RCT02310
RCT02320
RCT02330
RCT02340
RCT02350
RCT02360
RCT02370
RCT02380
RCT02390
RCT02400

```

CALL EQUATE(P5,NP5,P,NP)	RCT02410
CALL EQUATE(P55,NP55,PHAT,NPHAT)	RCT02420
CALL EQUATE(Q5,NQ5,Q,NQ)	RCT02430
CALL EQUATE(Q55,NQ55,QHAT,NQHAT)	RCT02440
PRINT *, ' '	RCT02450
CALL PRNT(P,NP,4H P,1)	RCT02460
PRINT *, ' '	RCT02470
CALL PRNT(PHAT,NPHAT,4H PHAT,1)	RCT02480
PRINT *, ' '	RCT02490
CALL PRNT(Q,NQ,4H Q,1)	RCT02500
PRINT *, ' '	RCT02510
CALL PRNT(QHAT,NQHAT,4H QHAT,1)	RCT02520
PRINT *, ' '	RCT02530
PRINT *, ' '	RCT02540
PRINT *, ' '	RCT02550
PRINT *, ' *** THE L-2 NORM = ',DIFF,' *****'	RCT02560
IF (DIFF .LT.EPSI)GO TO 130	RCT02570
PRINT *, ' '	RCT02580
C	RCT02590
C	RCT02600
C	RCT02610
CREATE H*	RCT02620
NTH4(1)=8	RCT02630
NTH4(2)=8	RCT02640
CALL UNITY(TH4,NTH4)	RCT02650
TH4(37)=P1(1)	RCT02660
TH4(38)=P1(2)	RCT02670
TH4(45)=P1(17)	RCT02680
TH4(46)=P1(18)	RCT02690
TH4(55)=P1(35)	RCT02700
TH4(56)=P1(36)	RCT02710
TH4(63)=P1(51)	RCT02720
TH4(64)=P1(52)	RCT02730
110 CALL MULT(TH3,NTH3,TH4,NTH4,TH5,NTH5)	RCT02740
NTH6(1)=12	RCT02750
NTH6(2)=8	RCT02760
CALL NULL(TH6,NTH6)	RCT02770
CALL JUXTC(TH5,NTH5,TH6,NTH6,TH7,NTH7)	RCT02780
NTH8(1)=4	RCT02790
NTH8(2)=16	RCT02800
CALL JUXT(TH7,NTH7,TH8,NTH8,H3,NH3)	RCT02810
C	RCT02820
C	RCT02830
C	RCT02840
C	RCT02850
C	RCT02860
CREATE MATRIX A*	RCT02870
FIND A31	RCT02880
CALL EQUATE(A51,NA51,TA51,NTA51)	RCT02890
CALL MULT(A51,NA51,TA51,NTA51,TA5,NTA5)	RCT02900
CALL SCALE(TA5,NTA5,TA51,NTA51,0.5)	RCT02910
CALL ADD(A51,NA51,TA51,NTA51,A31,NA31)	RCT02920
CALL EQUATE(A31,NA31,E1,NE1)	RCT02930
C	RCT02940
C	RCT02950
C	RCT02960
FIND A32	RCT02970
CALL TRANP(A31,NA31,A32,NA32)	RCT02980
C	RCT02990
C	RCT03000
C	
FIND A33	
CALL MULT(VI52,NVI52,C5,NC5,TA6,NTA6)	
CALL TRANP(C5,NC5,TC5,NTC5)	
CALL MULT(TC5,NTC5,TA6,NTA6,TA51,NTA51)	

C
C
C

CALL MULT(Q5,NQ5,TA51,NTA51,TA5,NTA5)
CALL SUBT(A31,NA31,TA5,NTA5,A33,NA33)

FIND A34

CALL TRANP(B5,NB5,TB5,NTB5)
CALL MULT(TB5,NTB5,P5,NP5,TA7,NTA7)
CALL MULT(RI52,NRI52,TA7,NTA7,TB5,NTB5)
CALL MULT(B5,NB5,TB5,NTB5,TA51,NTA51)
CALL SUBT(A31,NA31,TA51,NTA51,A34,NA34)

C
C
C

FIND A*

NZ1(1)=2
NZ1(2)=6
NZ2(1)=2
NZ2(2)=4
NZ5(1)=8
NZ5(2)=16
CALL NULL(Z1,NZ1)
CALL NULL(Z2,NZ2)
CALL NULL(TA5,NTA5)
CALL NULL(TH4,NTH4)
CALL NULL(Z5,NZ5)
CALL NULL(TH4,NTH4)
CALL JUXTC(A31,NA31,Z1,NZ1,X1,NX1)
CALL JUXTC(TA5,NTA5,A32,NA32,X21,NX21)
CALL JUXTC(X21,NX21,Z2,NZ2,X2,NX2)
CALL JUXTC(Z2,NZ2,A33,NA33,X31,NX31)
CALL JUXTC(X31,NX31,TA5,NTA5,X3,NX3)
CALL JUXTC(Z1,NZ1,A34,NA34,X4,NX4)
CALL JUXTR(X1,NX1,X2,NX2,X5,NX5)
CALL JUXTR(X5,NX5,X3,NX3,X6,NX6)
CALL JUXTR(X6,NX6,X4,NX4,X7,NX7)
CALL JUXTC(X7,NX7,TH4,NTH4,X8,NX8)
CALL JUXTR(X8,NX8,Z5,NZ5,A3,NA3)

C
C
C
C
C

CREATE Q*

FIND Q31

CALL UNITY(A32,NA32)
CALL GAUSEL(2,2,A51,2,A32,IERR)
CALL TRANP(A32,NA32,TA5,NTA5)
CALL MULT(R51,NR51,A32,NA32,TA51,NTA51)
CALL MULT(TA5,NTA5,TA51,NTA51,A31,NA31)
CALL ADD(P5,NP5,A31,NA31,A33,NA33)
CALL ADD(A33,NA33,P55,NP55,Q31,NQ31)

C
C
C

FIND Q32

CALL MULT(V51,NV51,TA5,NTA5,TA51,NTA51)
CALL MULT(A32,NA32,TA51,NTA51,A31,NA31)
CALL ADD(Q5,NQ5,A31,NA31,A33,NA33)
CALL ADD(A33,NA33,Q55,NQ55,Q32,NQ32)

C
C
C

FIND Q*

NZ6(1)=2
NZ6(2)=10

RCT03010
RCT03020
RCT03030
RCT03040
RCT03050
RCT03060
RCT03070
RCT03080
RCT03090
RCT03100
RCT03110
RCT03120
RCT03130
RCT03140
RCT03150
RCT03160
RCT03170
RCT03180
RCT03190
RCT03200
RCT03210
RCT03220
RCT03230
RCT03240
RCT03250
RCT03260
RCT03270
RCT03280
RCT03290
RCT03300
RCT03310
RCT03320
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RCT03490
RCT03500
RCT03510
RCT03520
RCT03530
RCT03540
RCT03550
RCT03560
RCT03570
RCT03580
RCT03590
RCT03600

	NZ7(1)=5	RCT03610
	NZ7(2)=4	RCT03620
	NZ8(1)=5	RCT03630
	NZ8(2)=3	RCT03640
	NZ9(1)=3	RCT03650
	NZ9(2)=9	RCT03660
	CALL NULL(TA51,NTA51)	RCT03670
	CALL NULL(X3,NX3)	RCT03680
	CALL JUXTC(Q31,NQ31,Z6,NZ6,X9,NX9)	RCT03690
	CALL JUXTC(TA51,NTA51,Q32,NQ32,X21,NX21)	RCT03700
	CALL JUXTC(X21,NX21,X3,NX3,X10,NX10)	RCT03710
	CALL JUXTC(Z7,NZ7,RI52,NRI52,X13,NX13)	RCT03720
	CALL JUXTC(X13,NX13,Z8,NZ8,X11,NX11)	RCT03730
	CALL JUXTC(Z9,NZ9,VI52,NVI52,X12,NX12)	RCT03740
	CALL JUXTR(X9,NX9,X10,NX10,X14,NX14)	RCT03750
	CALL JUXTR(X14,NX14,X11,NX11,X15,NX15)	RCT03760
	CALL JUXTR(X15,NX15,X12,NX12,X16,NX16)	RCT03770
	NX17(1)=12	RCT03780
	NX17(2)=4	RCT03790
	CALL NULL(X17,NX17)	RCT03800
	CALL NULL(TH8,NTH8)	RCT03810
	CALL JUXTC(X16,NX16,X17,NX17,X18,NX18)	RCT03820
	CALL JUXTR(X18,NX18,TH8,NTH8,Q3,NQ3)	RCT03830
C		RCT03840
C	CHECK IF A* IS ASYMPOTICALLY STABLE BY CSTAB	RCT03850
C		RCT03860
	DO 120 I=1,256	RCT03870
	P3(I)=0.0	RCT03880
	F3(I)=0.0	RCT03890
120	CONTINUE	RCT03900
	IOP(1)=0	RCT03910
	CALL CSTAB(A3,NA3,B3,NB3,F3,NF3,IOP,SCLE,DUMMY)	RCT03920
C		RCT03930
C	READY TO CALL RICNWT	RCT03940
C		RCT03950
	IOP(1)=0	RCT03960
	CALL RICNWT(A3,NA3,B3,NB3,H3,NH3,Q3,NQ3,R3,NR3,F3,NF3,P3,NP3,	RCT03970
	1IOP,IDENT,DISC,FNULL,DUMMY)	RCT03980
180	P5(1)=P3(1)	RCT03990
	P5(2)=P3(2)	RCT04000
	P5(3)=P3(17)	RCT04010
	P5(4)=P3(18)	RCT04020
	P55(1)=P3(69)	RCT04030
	P55(2)=P3(70)	RCT04040
	P55(3)=P3(85)	RCT04050
	P55(4)=P3(86)	RCT04060
	Q5(1)=P3(35)	RCT04070
	Q5(2)=P3(36)	RCT04080
	Q5(3)=P3(51)	RCT04090
	Q5(4)=P3(52)	RCT04100
	Q55(1)=P3(103)	RCT04110
	Q55(2)=P3(104)	RCT04120
	Q55(3)=P3(119)	RCT04130
	Q55(4)=P3(120)	RCT04140
	IF (ITE .GT. 1)GO TO 250	RCT04150
	DIFF=0.0	RCT04160
	DO 210 I=1,4	RCT04170
	DIFF=DIFF+(P5(I)-PP(I))**2+(P55(I)-PPH(I))**2	RCT04180
	DIFF=DIFF+(Q5(I)-QQ(I))**2+(Q55(I)-QQH(I))**2	RCT04190
210	CONTINUE	RCT04200

	GO TO 220	RCT04210
250	CALL SUBT(P3,NP3,TP4,NTP4,TP5,NTP5)	RCT04220
	DIFF =0.0	RCT04230
	DO 160 I =1,256	RCT04240
	DIFF=DIFF+TP5(1)**2	RCT04250
160	CONTINUE	RCT04260
220	DIFF=SQRT(DIFF)	RCT04270
	CALL EQUATE(P3,NP3,TP4,NTP4)	RCT04280
	IF(ITE .GT.50)GO TO 140	RCT04290
	GO TO 100	RCT04300
	CALL NORMS(256,16,16,TP5,1,RN1)	RCT04310
	CALL NORMS(256,16,16,TP5,1,RN2)	RCT04320
	CALL NORMS(256,16,16,TP5,1,RN3)	RCT04330
	DIFF=RN1	RCT04340
	IF (DIFF.LT. EPSI)GO TO 180	RCT04350
	DIFF=RN2	RCT04360
	IF (DIFF.LT. EPSI)GO TO 180	RCT04370
	DIFF=RN3	RCT04380
	IF (DIFF.LT. EPSI)GO TO 180	RCT04390
	IF(ITE .GT.15)GO TO 140	RCT04400
	GO TO 100	RCT04410
130	PRINT *, ' '	RCT04420
	PRINT *, ' ***** CONVERGES WITH TORELANCE = ',EPSI	RCT04430
	GO TO 150	RCT04440
140	PRINT *, ' ***** DIVERGES WITH OVER ',ITE,' ITERATIONS.'	RCT04450
	GO TO 164	RCT04460
150	CALL TRANP(C5,NC5,TC5,NTC5)	RCT04470
	CALL MULT(Q,NQ,TC5,NTC5,TA6,NTA6)	RCT04480
	CALL MULT(TA6,NTA6,VI52,NVI52,F,NF)	RCT04490
	CALL MULT(F,NF,C5,NC5,TM2,NTM2)	RCT04500
	CALL TRANP(B5,NB5,TM3,NTM3)	RCT04510
	CALL MULT(RI52,NRI52,TM3,NTM3,TM4,NTM4)	RCT04520
	CALL MULT(TM4,NTM4,P,NP,K,NK)	RCT04530
	CALL MULT(B5,NB5,K,NK,TM1,NTM1)	RCT04540
	CALL SUBT(E1,NE1,TM2,NTM2,E2,NE2)	RCT04550
	CALL SUBT(E2,NE2,TM1,NTM1,ACC,NACC)	RCT04560
	PRINT *, ' '	RCT04570
	PRINT *, ' '	RCT04580
	PRINT *, '***** COMPENSATOR MATRICES AFTER TRANSFORMATION'	RCT04590
	PRINT *, ' '	RCT04600
	CALL PRNT(ACC,NACC,4H ACC,1)	RCT04610
	CALL PRNT(F,NF,4H F,1)	RCT04620
	CALL PRNT(K,NK,4H K,1)	RCT04630
	PRINT *, ' '	RCT04640
	PRINT *, ' '	RCT04650
	PRINT *, '*****CPMPENSATOR MATRIX AC'	RCT04660
	CALL MULT(TRNI,NTRNI,ACC,NACC,A33,NA33)	RCT04670
	CALL MULT(A33,NA33,TRN,NTRN,AC,NAC)	RCT04680
	PRINT *, ' '	RCT04690
	CALL PRNT(AC,NAC,4H AC,1)	RCT04700
164	STOP	RCT04710
	END	RCT04720